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(54) **Processing image data.**

(57) Before being used in an interactive graphics end ronment, control points defining Bezier curves are processed to determine the curvature of the patch. This value is then used to determine the number of recursive iterations required to divide the patch into a plurality of renderable polygons.

A value is determined by considering the cosine of the turning angle between vectors connecting the control points of Bezier curves.

For each vector connecting the control points a respective vector of unit length is calculated. Cosine values are then calculated by producing the dot product of said unit vectors. Cosine values for two turning angles are calculated for each Bezier curve and a value indicative of curvature is determined by adding these cosine values together. The curvature of the whole patch is taken to be equivalent to the curvature of the most curved curve defining the patch.

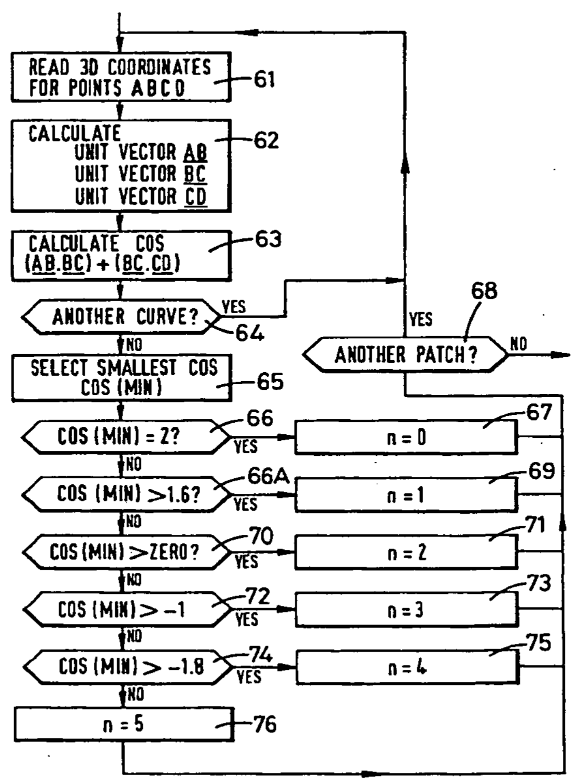


FIG.6

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The present invention relates to apparatus and methods for processing image data.

In particular, the present invention relates to apparatus and methods for displaying three-dimensional images. Furthermore, the present invention relates to an interactive graphics system in which objects are defined by areas and said areas are split into a plurality of polygons.

Graphics systems are known in which two-dimensional images are generated in response to data defining elements within a three-dimensional space. The final two-dimensional result may consist of a very large number of colored picture elements (pixels) which may be viewed on a monitor or printed onto an image carrying medium.

In interactive systems arranged to generate data representing a three-dimensional space, objects appear to move within three-dimensional space in response to input commands. Thus, in such systems, a machine is required to render a two-dimensional image from data representing a three-dimensional space repeatedly, as the position and/or orientation of objects, light sources and view position change in response to input commands. Typically, in an interactive environment, a machine is required to produce output images at a rate of between five to twenty per second.

Traditional machines of this type require a significant amount of computational overhead and, in the past, this requirement has placed significant constraints on system availability. Many techniques have been developed on behalf of the present Assignee, some of which provide the basis for patent applications assigned to the present Assignee, which reduce the computational overhead of an interactive three-dimensional graphics system. These techniques allow three-dimensional interactive graphic systems to be produced without requiring purpose built hardware.

In a system of this type, object geometry undergoes transformations in response to transformation matrices. The geometry is defined by the vertices of a plurality of polygons and, in order to effect a transformation of the object, it is necessary to perform the matrix transformation on each of said vertices. Thus, when a high number of polygons are present, a significant amount of computation is required in order to transform all of the object forming vertices.

As an alternative to transforming vertices, it is also known to transform complete areas of an object which are then rendered into polygons after the transformation has taken place. With this approach, it is not necessary to transform a large number of vertices, provided that sufficient data can be transformed to allow the object to be reconstituted after the transformation has taken place.

An area defined by Bezier curves and referred to as a Bezier patch is a suitable area for this type of transformation. Thus, a relatively large patch, capable of defining a large range of curves, may be identified by specifying sixteen control points, wherein each control point is either an end control point or an intermediate curvature control point for two of the eight Bezier curves defining the patch. A Bezier curve has finite length and is terminated at each of its ends by end control points. The intermediate curvature control points define the extent of curvature which occurs between the end points but the actual curve does not pass through the intermediate curvature control points. It should be noted that a Bezier patch defines a three-dimensional plane and the control points of the patch may be positioned anywhere within three-dimensional space. However, to effect rendering, it is necessary to divide the plane into polygons which are substantially flat or at least flat enough to effect a convincing render.

To effect rendering, it is known to recursively or iteratively sub-divide Bezier patches, effectively generating more points which are a closer approximation to the actual curve. Rendering may then be performed by using said points to define flat edged polygons, usually quadrilaterals or, preferably, triangles, whereafter individual pixels are allocated to the regions within the polygons by a process known as scan conversion.

However, the problem with known techniques for performing sub-division is that, after each iteration, it is necessary to determine whether sufficient divisions have been made. It is known that flatness tests may be performed after each sub-division has been executed, however, it is also known that the computational overhead for performing such a flatness test is relatively large, therefore, although the manipulations required to perform the sub-division itself do not place unrealistic constraints upon the processing capabilities available, the necessity to perform flatness testing as part of the sub-division process makes the use of Bezier patches unattractive. This is because the computational gain in not having to transform all of the polygons is substantially lost during the sub-division process for reconstituting polygons after a transformation has taken place.

According to an aspect of the present invention, there is provided a method of dividing an area into a plurality of polygons in a graphic system, by sub-division, wherein the number of divisions is predetermined by processing values indicative of curvature prior to initiating sub-division, so that said sub-division is carried out said predetermined number of times.

Thus, an advantage of the present invention is that a determination is made as to the number of sub-divisions required before entering interactive control, wherein the efficient use of processing power is critical.

It is unnecessary in accordance with the present invention, to perform flatness testing after each sub-

division.

In a preferred embodiment, the area is defined by Bezier curves, wherein each Bezier curve is defined by a pair of end control points and a pair of curvature control points. Preferably, said value indicative of curvature is a value indicative of an angle between vectors connected to said curvature control points.

The invention will now be described by way of example only, with reference to the accompanying drawings, of which:

Figure 1 shows an interactive three-dimensional graphics system, including a processor for manipulating three-dimensional data and generating two-dimensional data;

Figure 2 shows a Bezier curve, the control points for defining said curve and the equations for calculating points on the curve from the position of said control points; Figure 3 shows a Bezier patch, defined by Bezier curves;

Figure 4 illustrates the operation of an interactive three-dimensional graphics system, embodying the present invention.

Figures 5 and 6 illustrate a preferred procedure for calculating the curvature of a Bezier patch and for determining the number of iterations required to divide the patch into polygons;

Figure 7 illustrates the procedure for determining the order in which patches are to be rendered;

Figure 8A shows conventional polygonisation of a Bezier patch; and

Figure 8B shows a Bezier patch polygonisation produced by an embodiment of the present invention.

A system for processing image data representing three-dimensional objects is shown in Figure 1. A processor 15 is arranged to write data to and read data from local memory. Data stored in the processors' memory defines three dimensional image data, two dimensional image data and instructions to the processor 15.

The processor 15 receives input data, from input devices consisting of a manually operable keyboard 17 and a position sensitive device, such as a mouse, a trackerball 18 or a digitising stylus etc.

Two-dimensional images are displayed on a visual display unit 19, which receives output image data at video rate by raster scanning a frame buffer, often provided with proprietry display units. The visual display unit has a definition of, typically, one thousand lines with one thousand pixels on each line, requiring a frame buffer with one million pixel locations. For the bulk transfer of program data and image data, a mass storage device 20 is provided, such as a hard magnetic disk, optical disk or tape drive etc.

In the present embodiment, data defining geometry is stored in the form of control points defining Bezier patches, which may be manipulated in three-dimensional space. Thereafter, once a viewing position has been selected for rendering in two-dimensions, each Bezier patch is broken down into a plurality of vertices defining polygons, whereafter pixel values are calculated by scanning the area of each polygon.

A parametric Bezier curve 25 is shown in Figure 2, consisting of a locus of points moving from an end control point A to another end control point D, in response to the position of curvature control points B and C. The locus of points are calculated over the parameter space t=0 to t=1 and, for each value of t, a point may be calculated which receives contributions from the positions of points A, B, C and D. The blending contributions are determined from a bi-cubic function known as the Bernstein blending function, detailed below the Bezier curve in Figure 2. Thus, points along the curve are calculated by substituting the x, y and z coordinate values of the control points A, B, C and D into the blending function for calculating new values for x, y and z, as t varies between zero and unity.

An attractive feature of Bezier curves,.within an interactive graphics environment, is that the curve can be drawn to any requried resolution from input data consisting of the coordinates for points A, B, C and D. Thus, the whole curve can be manipulated in three-dimensional space by manipulating the positions of just the four control points which define it. Thereafter, rendering to create a displayable image can be performed at any desired resolution, by dividing the surface into flat polygons and then rendering each polygon.

As shown in Figure 2, when points A, B, C and D are connected by vectors AB, BC and CD it can be seen that the actual curve is tangential to vector AB at point A and tangential to vector CD at the end control point D. It can also be seen that the position of points B and C controls the extent of the curvature and these points are therefore referred to herein as curvature control points.

In a system such as than shown in Figure 1, data defining the shape of the Bezier curve 25 consists of three-dimensional coordinate locations for the control points A, B, C and D. In order to render such a curve it is necessary to approximate its shape by straight line segments defining renderable flat polygons. As previously stated, an approach would be to calculate points using the blending function detailed in Figure 2, although problems with this approach include deciding how many points need to be calculated and executing the demanding calculations.

In the present embodiment, areas are divided into a plurality of polygons by recursive or interative subdivision and this technique will be detailed with reference to the single Bezier curve shown in Figure 2. A first approximation to the actual Bezier curve 25 would consist of vectors AB, BC and CD joining the control points A, B, C and D. As readily appreciated

from the example shown in Figure 2, such an approximation would rarely provide satisfactory results, given that the curvature control points may be a significant distance away from the locus of the actual curve.

Sub-division is performed by identifying an intermediate point E between points A and B. This point is easily calculated because the x coordinate of E is the average of the x coodinates for points A and B and similarly averaged values can be determined for the y and z coordinates. Thus, a similar intermediate point F is located halfway along the vector BC and a third intermediate point G is identified halfway along the vector CD. This process is continued by identifying an additional point H halfway along vector EF and point I halfway along vector FG, from which a new vector HI is defined. . Finally, point J is calculated as a point halfway along vector HI.

Points E, H, I and G do not lie on the Bezier curve 25 but point J is a point of the Bezier locus. Furthermore, the Bezier curve 25 connecting points A to D may now be considered as two Bezier- curves, a first connecting points A to J and a second connecting point J to D. Thus, the curve not only passes through point J but, at point J, it is also tangential to the vector HI. Thus, point J provides a new end control point for two Bezier curves while points E and H provide a first set of curvature control points and points I and G provide a second set of curvature control points.

From a rendering point of view, an initial approximation consisting of the three straight lines AB, BC and CD has being improved by the generation of six straight lines AE, EH, HJ, JI, IG and GD.

In some situations, this first iteration will not be sufficient. However, a better approximation to the curve 25 may be generated by considering the curve to be made up of two separate Bezier curves, a first defined by control points A, E, H and J and a second defined by control points J, I, G and D. Thus, the subdivision procedure, performed and illustrated in Figure 2 for points A, B, C and D, may be repeated firstly for points A, E, H and J and secondly for points J, I, G and D. Thus, this sub-dividing could be repeated to the resolution limits of the system and the problem with the technique, as previously identified, is that of deciding how many sub-divisions are to be performed.

After each division it is possible to perform a flatness test, as described in "Computer Graphics Principles and Practice", second edition, pp 513-514 by Foley, van Dam, Finer and Hughes. However, if flatness tests are performed each time, the overall computational overhead becomes excessive and the computational reduction gained by using Bezier curves is substantially lost, due to the repeated flatness testing.

A Bezier curve, consisting of a locus of points is defined in two dimensions. However, A group of Bezier curves combined to define a plane, referred to as a Bezier patch, includes control points which may be positioned anywhere in three-dimensional-space. The control points for a Bezier patch of this type are shown in Figure 3, in which points A1, B1, C1 and D1 define a Bezier curve, points A2, B2, C2 and D2 define a second curve, points A3, B3, C3, D3 define a third curve and points A4, B4, C4 and D4 define a fourth curve. In addition, a second set of curves is defined by points A1, A2, A3, A4, points B1, B2, B3 and B4, points C1, C2, C3, C4 and points D1, D2, D3 and D4. Thus, the patch is defined by a total of eight Bezier curves in three-dimensional space, configured from a total of sixteen control points, in which each of said points provides a control point for two of said curves. Some control points (A1, D1, A4 and D4) are end control points for two curves, while some (B2, C2, E3, C4) are curvature control points for two curves, while the reminder are end contol points for one curve but curvature control points for the other.

As can be seen from Figure 3, vectors connecting the control points divide the patch into a total of nine segments. However, it should also be understood that the lines shown connecting points in Figure 3 do not actually lie on the curve itself but are equivalent to vectors AB, BC and CD of Figure 2

Thus, the nine polygons shown in Figure 3, formed by connecting the control points of the Bezier patch, could be used to provide a first approximation to the actual patch, for rendering purposes, in the same way in which vectors AB, BC and CD form a first approximation to the Bezier curve 25 in Figure 2.

This division consists of connecting all adjacent control points and illustrates the accepted way of dividing the patch into renderable polygons. Furthermore, more accurate polygonization can be provided by sub-dividing each Bezier curve of Figure 3, wherein each curve is divided into a pair of curves, having a common end control point, similar to point J in Figure 2. Thus, by sub-dividing each curve, each quadrilateral polygon is divided into four smaller quadrilateral polygons, resulting in a total of 36 polygons for the whole patch.

As stated with reference to Figure 2, the newly calculated point J is a point which does actually lie on the Bezier curve. Similarly, when considering a surface, newly calculated point K at the centre of the surface is a point which actually does lie on the surface. Thus, the patch may be considered as being made up of four smaller patches and the sub-dividing process may be repeated for each of these four patches.

As previously stated, a known problem with dividing patches in this way is in performing tests to determine whether, after each division, a further division is required. In the present embodiment pre-processing is performed on each Bezier patch to determine how many iterations are required for that patch, so that, after transformation into two-dimensional viewing space, sub-division is performed n times for

each patch, where the value n for that particular patch was precalculated.

The operational stages performed by the apparatus shown in Figure 1 and embodying the present invention are shown in Figure 4.

Geometry data, defining the shape of objects, is stored in the form of control points for Bezier patches of the type shown in Figure 3. Each patch includes a total of sixteen vertices, A1 to D4 from which the overall shape of the patch for any orientation in three-dimensional space and from any viewing position, can be determined.

In Figure 4, steps 42 to 44 are pre-processes performed prior to the initiation of interactive operation. The pre-processes calculate data, relevant to the objects under consideration, so as to reduce computational demands during interactive operation: it being noted that many of the processing requirements forming part of the interactive loop are required to be performed during each iteration, therefore substantial savings can be made by reducing the amount of processing required within the iteractive loop.

At step 42, a determination is made as to the number of iterations required to produce a sufficient number of polygons for each Bezier patch. Thus, although polygons are produced using the previously described sub-division technique, it is not necessary, during this process, to determine whether sufficient divisions have been made. The level of divisions required is pre-calculated and whenever polygons are required to be produced from Bezier patches, this data is recalled and sub-division is performed n times, where n is generated during the pre-processing period.

At step 43, the polygons are generated in modelling space, also referred to as object space, so that, in modelling space, the object is defined by its Bezier control points and also by polygons, produced by n sub-divisions. Furthermore a unit normal vector is calculated for each polygon, allowing lighting calculations to be performed in modelling space.

At step 44, calculations are made to determine the order in which patches should be rendered. An example of a technique for assessing the order in which the polygons should be rendered is detailed in European Patent publication number 0 531 157 The technique detailed in this Patent Application is employed upon the polygons produced at step 43. This information is then used to determine the order in which whole patches should be rendered, wherein the first occurence of a polygon from a particular patch in the priority order, establishes the priority for the whole patch.

After the termination of step 44, the system is ready to enter interactive operation, in which objects, light sources and the position of the viewer appear to move within a synthesized three-dimensional space, in response to input commands.

On initiating interactive operation, objects (defined by Bezier patches), light sources and a viewing position are defined and the objects are projected onto a two-dimensional viewing plane. Each iteration of the interactive loop consists of receiving input data defining translations within three-dimesional space, projecting three-dimensional data onto a two-dimensional viewing plane and rendering the two-dimensional data into an array of pixels. Given that objects are constructed from a plurality of patches, the order in which said patches are rendered depends upon the orientation of the object and the veiwing position. At step 44, lists are constructed specifying patch rendering orders for particular view orientations. At step 46 the view orientation of the object is determined and this information, in addition to data determined at step 44, is used to calculate the order in which the patches themselves are rendered, thus flow line 47 represents the transfer of information from step 44 to step 46.

At step 48, control points for the first patch to be rendered, as determined at step 46, are transformed, under the operation of a transformation matrix, to two-dimensional viewing space.

At step 49, the control points transformed into two-dimensional viewing space are sub-divided n times, where the value n was previously calculated at step 42 and the transfer of information from step 42 to step 49 is illustrated by flow arrow 50.

When the whole patch has been scan converted at step 51, a question is asked at step 52 as to whether further patches are present in the scene. If this question is answered in the affirmative, control is returned to step 48, which reads the next set of control points for transformation into two-dimensional space. Thus, this reading of control points, with subsequent sub-division and scan conversion is repeated until all of the patches have been reduced to pixels. This results in the question asked at step 52 being answered in the negative and, at step 53, calculated pixel values are written to a frame buffer 54.

In addition to being written to the frame buffer at interactive rate, the frame buffer 54 is also read repeatedly, at step 55, at video rate, thereby generating a video output signal for the monitor 19.

At step 54, interactive input commands are read and at step 55 new transforms are calculated in response to the interactive inputs received at step 54. Thus, in response to the interactive input supplied at step 54, modified transformations are effected at step 48.

After recalculating the transformations, control is returned to step 45, thereby completing the interactive loop. If, in response to interactive inputs received at step 54, the position of an object has not changed with respect to the position of any light source, lighting calculations are reused at step 45.

Curvature is determined by considering each Be-

zier curve making up the patch and a notional value representing the curvature of the patch is adopted based upon the most curved Bezier curve of the patch.

A Bezier curve similar to the curve shown in Figure 2, is shown in Figure 5. Pre-processing performed at step 42 involves considering the positions of points A, B, C and D, that is to say, the control points defining the Bezier curve rather than the locus of the Bezier curve itself. The points A, B, C and D are considered as connected by vectors AB, BC and CD. Vector AB has a direction defined by that taken to move from A to B. Similarly, vector BC has a direction, being that required to move from B to C, while the direction of vector CD is that required to move from point C to point D. When considered as a combined movement from point A to D via point B and point C, a turn is encountered at point B and a similar turn is encountered at point C. These turns may be defined by turning angles t1 and t2 respectively. Furthermore, the extent of these turning angles t1 and t2 are related to the curvature of the Bezier curve itself, therefore an analysis of turn angles t1 and t2 provides a basis for calculating the curvature of the patch, which is then used to determined the number of sub-divisions required to divide the patch into a suitable number of polygons.

Each patch is considered in turn and each set of control points (a total of eight sets) defining the Bezier curves for the patch are considered in turn. Thus, referring to the control points shown in Figure 5, vectors AB, BC and CD are converted to define vectors having equivalent directions but of unit length. Thus, the converted vector derived from vector AB will be identified herein as $\underline{AB}$ with similar representations $\underline{BC}$ and $\underline{CD}$ being used to represent the unit vectors derived from vectors BC and CD respectively.

A value representing the curvature of the Bezier curve is calculated by forming the sum of the dot product between unit vectors $\underline{AB}$ and $\underline{BC}$ and the dot product between unit vectors $\underline{BC}$ and $\underline{CD}$ . Being of unit length, the result of calculating the dot product of $\underline{AB}$ and $\underline{BC}$ will be equal to the cosine of angle t1. Similarly, the dot product of $\underline{BC}$ with $\underline{CD}$ will be equal to the cosine of angle t2.

In theory, angles t1 and t2 may have any value from zero to a full 360 degrees. A numerical value is calculated representing curvature by considering the cosine of the turning angle determined, as previously stated, by calculating the dot product of unit vectors. A major advantage of using the cosine function is that a positive turn angle in excess or 180 degress yields the same result as its negative equivalent. Thus, the cosine function only measures the amount of turn and is not influenced by the direction of the turn.

The Bezier curve is least curved when angle t1 is small (or reflex) therefore the curve is less curved when the cosine of t1 is positive. Similarly, the curve becomes more curved as the cosine value becomes negative, with the extreme condition being at 180 degrees, where the cosine is -1.

The overall curvature of the curve is determined by adding together the cosine of angle t1 with the cosine of angle t2, thereby giving curvature values which range from +2 (least curved) to -2 (most curved).

The curvature of the whole patch is determined by the most curved curve defining the patch. Thus, the patch as a whole will be accorded a notional curvature value equal to the lowest (most negative) value calculated for the Bezier curves making up the patch. This measure of notional curvature provides a basis for determining the number of sub-divisions required to divide the patch into renderable polygons. The number of sub-divisions performed may vary from machine to machine and specific values for one type of machine for a particular environment may be calculated emperically. In the present embodiment the maximum number of sub-divisions which may be performed is five.

The operations performed at step 42 in Figure 4 are detailed in Figure 6. A first patch is selected and a first Bezier curve of said patch is considered at step 61, which reads the three-dimensional coordinates for the four control points defining the Bezier curve, A, B, C, D. At step 62 unit vectors $\underline{AB}$ , $\underline{BC}$ and $\underline{CD}$ are calculated by considering vectors $\overline{AB}$, $\overline{BC}$ and $\overline{CD}$. As previously stated, each unit vector has a direction equivalent to the vector from which it is derived but is of unit length.

At step 63 the combined cosine value COS is calculated as the sum of the dot products between $\underline{AB}$ with $\underline{BC}$ and $\underline{BC}$ with $\underline{CD}$ .

At step 64, a question is asked as to whether there is another curve (of the eight curves defining the patch) to be considered within the patch and if this question is answered in the affirmative, control is returned to step 61 and the coordinate values A, B, C, D for the next curve are considered.

If the question asked at step 64 is answered in the negative, the smallest COS value calculated for the patch is selected, identified herein as COS (MIN). The curve having the smallest COS value, the smallest possible value being -2, has the greatest curvature and this curve is therefore selected as being the one defining the nominal curvature of the patch as a whole.

At step 66, a question is asked as to whether the value for COS selected at step 65 is equal to 2, representing a perfectly non-curved surface. If this question is answered in the affirmative, n is set equal to zero at step 67 and a question is asked at step 68 as to whether any more patches are to be considered. The value n represents the number of sub-divisions to be performed and for a perfectly flat surface, no divisions are required.

If the question asked at step 66 is answered in the negative, that is to say, COS (MIN) has a value less than 2, a question is asked at step 68 as to whether COS (MIN) is greater than 1.6. If this question is answered in the affirmative, n is set equal to 1 at step 69 and control returns to the question at step 68.

If the question asked at step 68 is answered in the negative, a question is asked at step 70 as to whether COS (MIN) is greater than zero. If this question is answered in the affirmative, n is set equal to 2 at step 71 and control returns to the question asked at step 68.

If the question asked at step 70 is answered in the negative, a further question is asked at step 72 as to whether COS (MIN) is greater than -1. If this question is answered in the affirmative, n is set equal to 3 and control returns to the question raised at step 68.

Finally, if the question asked at step 72 is answered in the negative, a question is asked at step 74 as to whether COS (MIN) is greater than -1.8. If this question is answered in the affirmative, n is set equal to 4 at step 74 and control is returned to the question at step 68. If the question raised at step 74 is answered in the negative, n is set equal to 5 at step 76 and control is returned to the question raised at step 68.

In this example, n, the number of sub-divisions performed within a particular patch, may have any value ranging between zero and five. However, the maximum number of sub-divisions carried out by the system may be selected so as to suit any particular application. Similary, the judgements made as to the relationship between COS (MIN) and the number of iterations required may be arbitrarily chosen for any particular application.

If the question asked at step 68 is answered in the affirmative, control is returned to step 61, the first set of coordinates for the next Bezier patch are read and the process repeated. Eventually, the question asked at step 68 will be answered in the negative, thereby allowing the pre-processing procedure to continue to step 43.

As shown in Figure 4, step 44 determines the patch rendering order, with reference to polygons derived from the patch. The process performed at step 44 is detailed in Figure 7 in which, at step 81, patch data is sub-divided n times to produce polygons in modelling space. All of the patches are processed in this way to produce an arbitrary list of polygons. At step 82 a topological sort is performed on the polygons, as described in European Patent publication number 0 531 157 the full contents of which are included herein as part of the present disclosure. Thus, at step 82 a polygon order list is produced, which lists the polygons in the order in which they should be rendered, for a particular set of viewing parameters. A plurality of lists are produced and a particular list is selected during interactive operation. Thus, referring to Figure 4, the lists are produced at step 44 and the particular list required is selected at step 46, as part of the interactive process.

At step 83 a question is asked as to whether another polygon exists in the polygon order list and, when answered in the negative, process 44 (Figure 4) terminates, allowing control to enter the interactive loop.

When the question raised at step 83 is answered in the affirmative, the next polygon from the polgyon order list is read at step 84 and applied to the patch order list. Thus, in addition to including data identifying the particular polygon, the polygon order list also includes an identification of the polygon's originating patch. Thus, it is this information which is relevant to the patch order list, produced at step 84.

At step 85 all occurences of polgons belonging to the same patch as that identified at step 84 are deleted from the polygon lists produced at step 82. Thus, the procedure is only interested in identifying a set of polygons derived from a particular patch once, so that the patch may be added to the patch order list at step 84.

Thereafter, control is returned to the question at step 83 and if polygons still exist in the polygon order list, step 84 is repeated. On this occurence, all entries relating to previously identified patches will have been deleted from the polygon order list, such that the next polygon read at step 84 must relate to another patch. Thus, another patch will always be added to the patch order list and again all other occurences of polygons from the same patch are deleted from the polygon order list.

When an object includes a concavity, viewing angles exist from which a forward facing polygon will lie in front of another forward facing polygon. In this situatation, the outer most polygon of the two will, from some angles, occlude the innermost polygon. In practice, the total number of such occlusions is quite low.

At step 82, a sorter operates to sort polygons in two stages. In a first stage, polygons which may potentially occlude others are separated from those which will not. Of the polygons where the potential for occlusion exists, every polygon is compared with that polygon to determine whether the other polygons lie behind or in front of the plane of that polygon. A polygon is considered to lie in front of the plane if all of its vertices lie in front of the plane and, to avoid indeterminacy, a polygon is also considered to lie in front of the plane if some vertices are in front and other are in the plane (within prescribed tolerances) or if all are in the plane.

The sorter takes in turn each polygon in the list and derives the coefficients of the equation defining the plane, that is $Ax + By + Cz + D = 0$, from the coordinates of vertices defining the plane. The sorter then examines each other polygon in turn and determines, for that polygon, whether all the modes of that

polygon satisfy the inequality, to the effect that Ax + By + Cz + D is greater than zero. If the inequality is met for all vertices of the first compared polygon, that polygon is considered to lie wholly in front of the polygon under consideration and the sorter proceed to the next other polygon. If all nodes are coplaner or if the second polygon lies wholly behind the plane of the first, when viewed normal to that plane, that polygon is considered to lie wholly behind the polygon under consideration. The sorter creates a new table containing an entry for each polygon in the table, each entry comprising a set or list of the numbers of the other polygons which lie behind that polygon. Each time every node of a polygon lies behind the plane of another, an indication of the identity of that polygon is recorded in a "behind" list.

Further details of the procedure for producing the topological sort step 82 are disclosed in the aforesaid copending application which, as previously stated, the whole of which forms part of the present disclosure.

Referring to Figure 4, after the patch has been sub-divided n times, scan conversion takes place at step 51 in order to generate pixels. Pixel values are generated on a polygon by polygon basis, therefore each Bezier patch is divided into a plurality of flat edged polygons.

Figure 8A and Figure 8B both show an array of 16 Bezier control points defining a Bezier patch produced after the n sub-divisions have been carried out. Thus, after one division, the patch shown in Figure 8A will have been divided into an array of a total of four similar patches. Again, after two divisions a patch shown in Figure 8A will have been divided into of a total of 16 patches and so on.

Each Bezier patch produced by sub-division may be divided into polygons in a substantially similar manner. Thus, in accordance with the conventional approach to rendering Bezier patches, each control point of the patch is notionally connected to its nearest neighbours to produce nine quadrilaterals. Thereafter, each of said quadrilaterals is divided across a diagonal to yield two triangles, therefore each Bezier patch is divided into a total of eighteen renderable polygons.

An alternative for dividing the patch shown in Figure 8A is detailed in Figure 8B. In Figure 8B the Bezier patch, having control points at equivalent positions to the patch shown in Figure 8A, is divided into renderable polygons by connecting the four corner control points A1, D1, D4 and A4 to produce a quadrilateral. These selected control points may be considered as a set which are all end control points for two Bezier curves defining the patch. This quadrilateral is then divided into two renderable triangles by connecting point A1 to D4.

Referring back to Figure 2, the rendering procedure performed in Figure 8A for a patch is equivalent to estimating the Bezier curve 25 by a line ABCD. As can be seen from Figure 2, this produces an estimate which lies outside curve 25, that is to say it is larger than curve 25. The rendering solution shown in Figure 8B is effectively equivalent to connecting points A and D directly. Again this only estimates the shape of curve 25 but on this occasion the estimate is within the curve 25, that is to say, it produces an estimate which is smaller than the curve 25.

As further sub-division are effected, both estimates to the patch come closer to the actual patch. However, irrespective of the number of divisions made, the conventional estimate, of the type shown in Figure 8A, will lie outside the patch, whereas the alternative estimate, as shown in Figure 8B, will lie inside the patch. Thus, again referring to Figure 2, an estimate produced on the second sub-division would connect point A to point J directly and connect point J to point D directly which, as will be appreciated, provides a significantly better estimate to the position of curve 25.

In the embodiment, an operator is given a choice as to whether polygonisation is to be performed in accordance with the conventional technique as detailed in Figure 8A or in accordance with the present invention as detailed in Figure 8B. Thus, the operator is given two rendering possibilities, one which produces polygons which lie outside the actual Bezier curve itself and another which will produce polygons lying within the Bezier curve itself. It will be appreciated that the preferred solution to producing polygons will often be dependent upon the overall application being executed by the operator.

In the known approach to dividing the Bezier patch by connecting control points, as shown in Figure 8A, all of the control points are connected. However, the essential difference to the alternative approach is that only a selected set of control points are connected. Thus, in addition to connecting points A1, D1, A4 and D4, points B2, C2, B3 and C3 could also be connected. Thus, the set of connected points may be defined as those points which provide end control points for two Bezier curves along with control points which provide curvature control points for two Bezier curves, while exeluding the control points which provide an end control point for one Bezier curve and a curvature control point for another Bezier curve. Furthermore, it will be appreciated that other sets may be selected from the available control points, for connecting so as to form the basis of defining renderable polygons.

## Claims

1. A method of dividing an area into a plurality of polygons in a graphics system, by sub-division, characterised in that the number of divisions is

predetermined by processing values indicative of curvature prior to initiating sub-division, so that said sub-division is carried out said predetermined number of times.

2. A method according to claim 1, wherein the area is defined by Bezier curves, said Bezier curves having a pair of end control points and a pair of curvature control points.

3. A method according to claim 2, wherein said value indicative of curvature is a value indicative of an angle between vectors connected to curvature control points.

4. A method according to claim 3, wherein said angle is the turn angle of said vectors.

5. A method according to claim 3, wherein said value indicative of an angle between said vectors is determined from the cosine of the turn angle.

6. A method according to claim 5, wherein said cosine is calculated by calculating the dot product of said vectors.

7. A method according to claim 3, wherein said value indicative of curvature is a value indicative of angles defined by vectors connected to both of said curvature control points.

8. A method according to any preceding claim, wherein said area is defined by curves and the curvature of the area is taken as being determined by the curve of highest curvature.

9. A method according to any preceding claim, wherein said graphics system is an interactive three-dimensional system arranged to model the movement of objects in three-dimensional space in response to input commands, wherein said number of sub-divisions for each area is predetermined, three-dimensional object data defining said areas are projected to form two-dimensional data and the predetermined number of sub-divisions are generated in response to said two-dimensional data.

10. A method according to claim 9, wherein lighting calculations are made for each polygon in three-dimensional space, prior to reconstituting said polygons in two-dimensional space.

11. Apparatus for dividing an area into a plurality of polygons in a graphic system, by sub-division, characterised by means (15) for predetermining the number of divisions required by processing values indicative of curvature prior to initiating sub-division, so that said sub-division is carried out said predetermined number of times.

12. Apparatus according to claim 11, wherein the area is defined by Bezier curves, said Bezier curves being defined by a pair of end control points and a pair of curvature control points.

13. Apparatus according to claim 12, including means for determining an angle between vectors connected to said curvature control points.

14. Apparatus according to claim 13, wherein said angle is the turn angle of said vectors.

15. Apparatus according to claim 13, wherein said value indicative of said angle between said vectors is determined from the cosine of the turn angle.

16. Apparatus according to claim 15, wherein said cosine is calculated by calculating the dot product of said vectors.

17. Apparatus according to claim 13, wherein said value indicative of curvature is a value indicative of angles defined by vectors connected to both curvature control points of each Bezier curve.

18. Apparatus according to claim 11, wherein said area is defined by curves and the curvature of the area is taken as being dependent upon the curve of highest curvature.

19. Apparatus according to claim 11, forming part of an interactive three-dimensional graphics system arranged to model the movement of objects in three-dimensional space in response to input commands, wherein said number of sub-divisions for each area is precalculated, three-dimensional object data defining said areas are projected to form two-dimensional data and the predetermined number of sub-divisions are executed upon the transform two-dimensional data.

20. Apparatus according to claim 19, wherein lighting calculations are made for each polygon in three-dimensional space, prior to reconstituting said polygons in two-dimensional space by said process of sub-division.

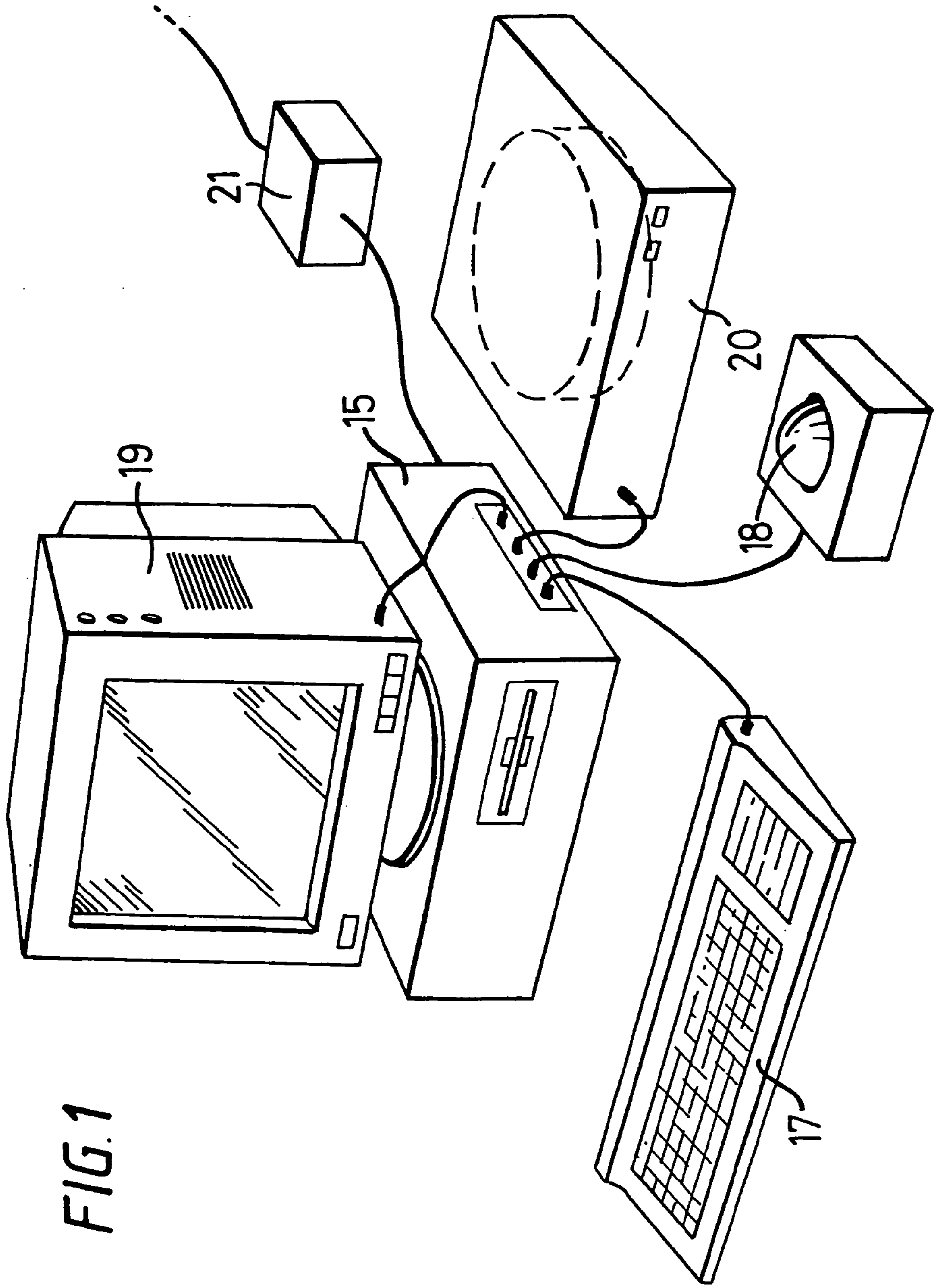
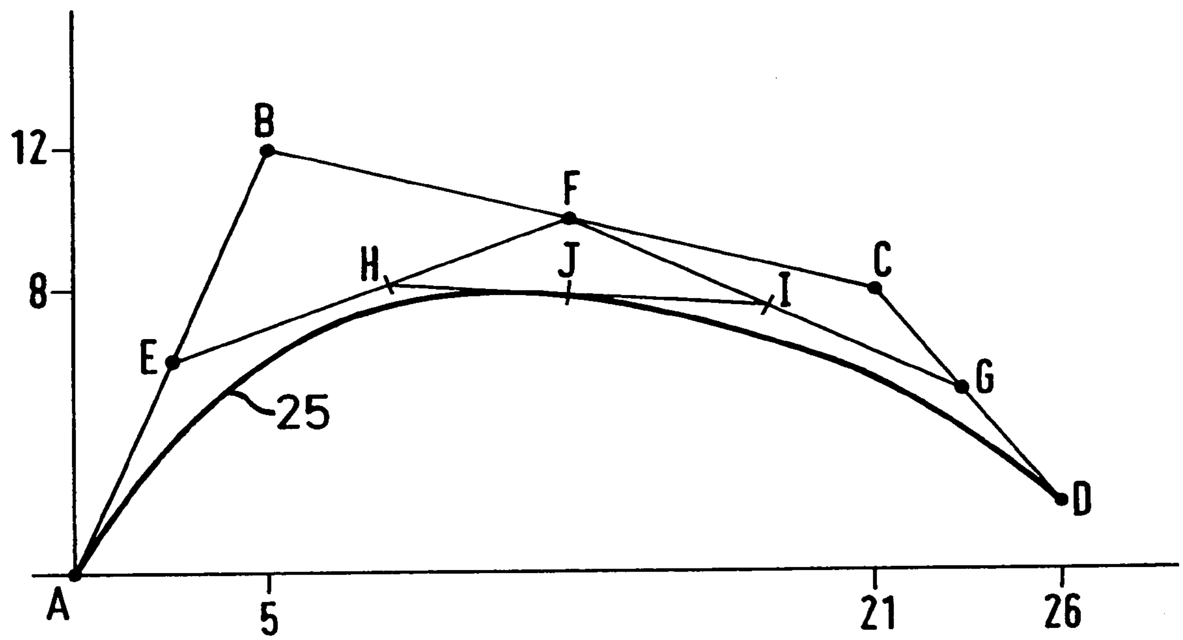



FIG.1




$$x = (1-t)^3 x_A + 3t(1-t)^2 x_B + 3t^2(1-t) x_C + t^3 x_D$$

$$y = (1-t)^3 y_A + 3t(1-t)^2 y_B + 3t^2(1-t) y_C + t^3 y_D$$

$$z = (1-t)^3 z_A + 3t(1-t)^2 z_B + 3t^2(1-t) z_C + t^3 z_D$$

For $t$: $0 \leqslant t \leqslant 1$

*FIG. 2*

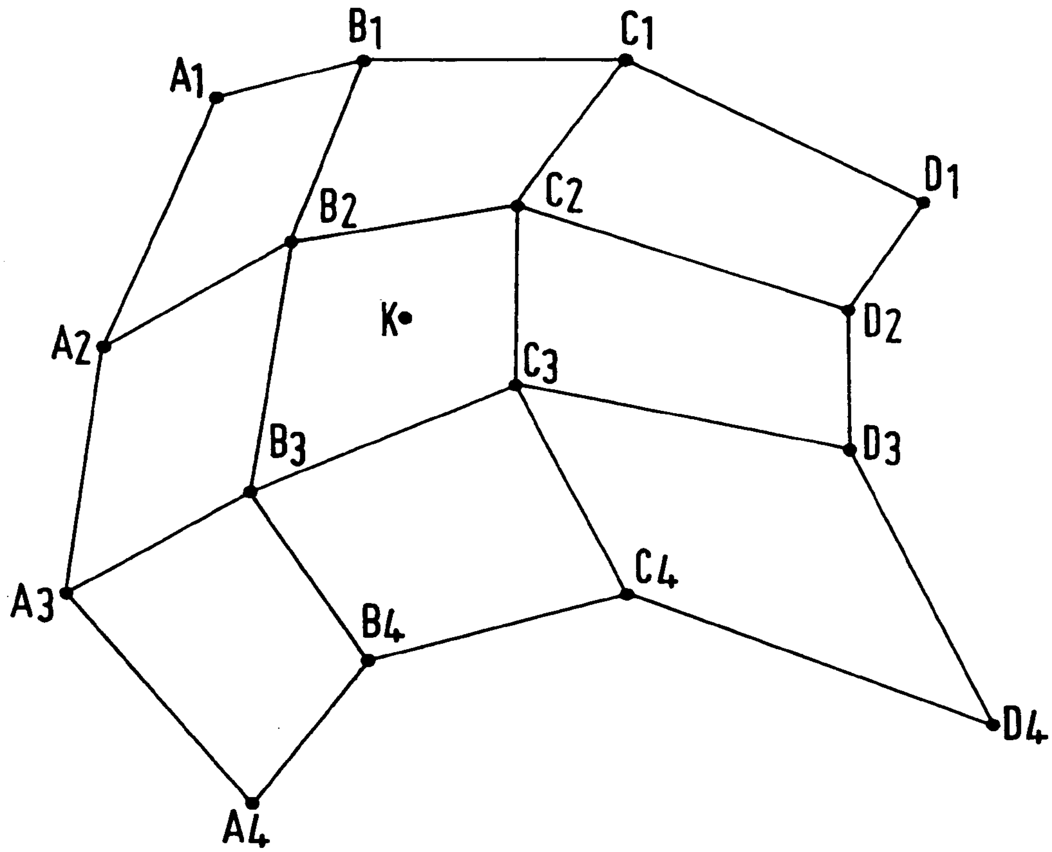



FIG. 3

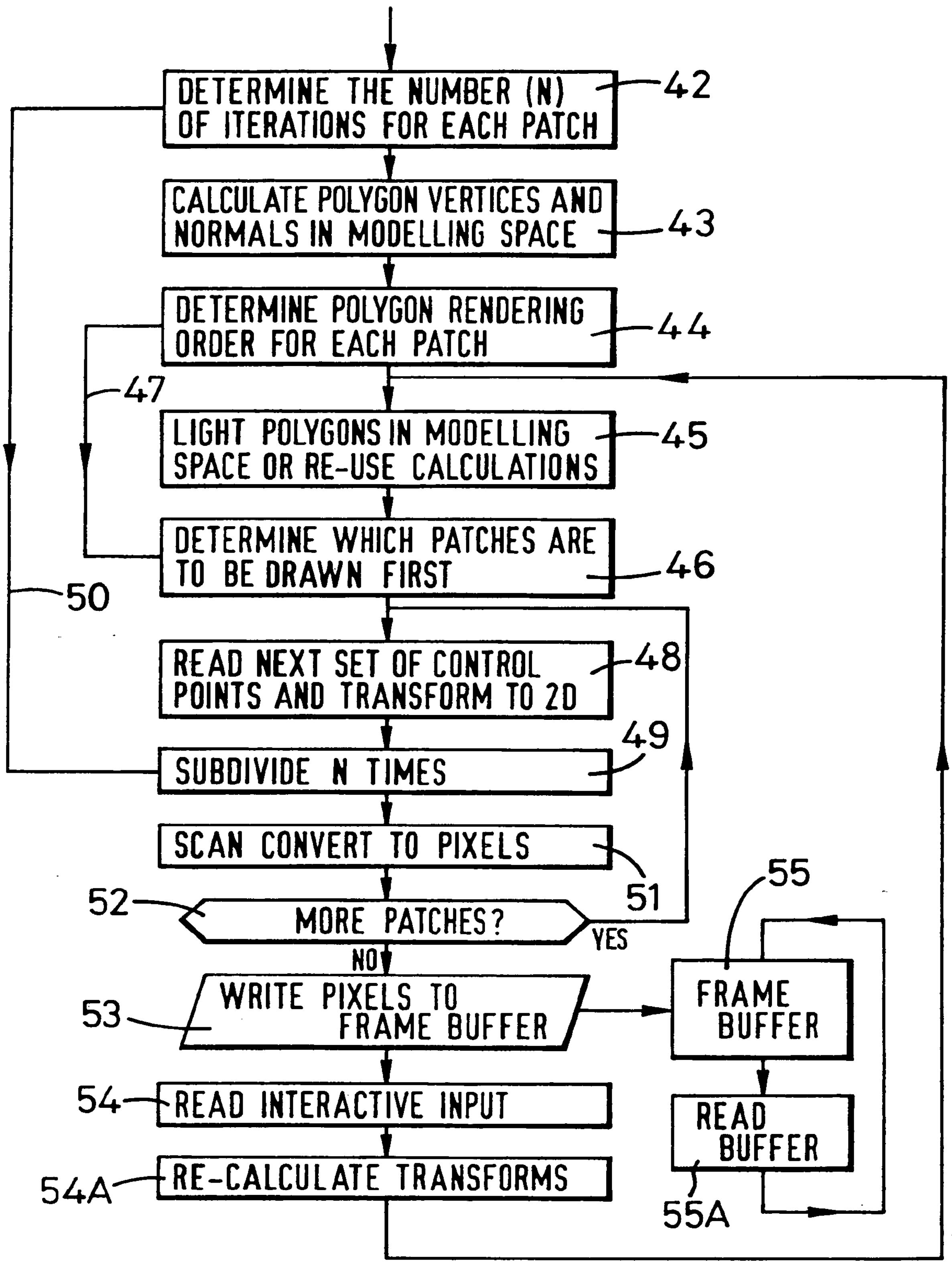
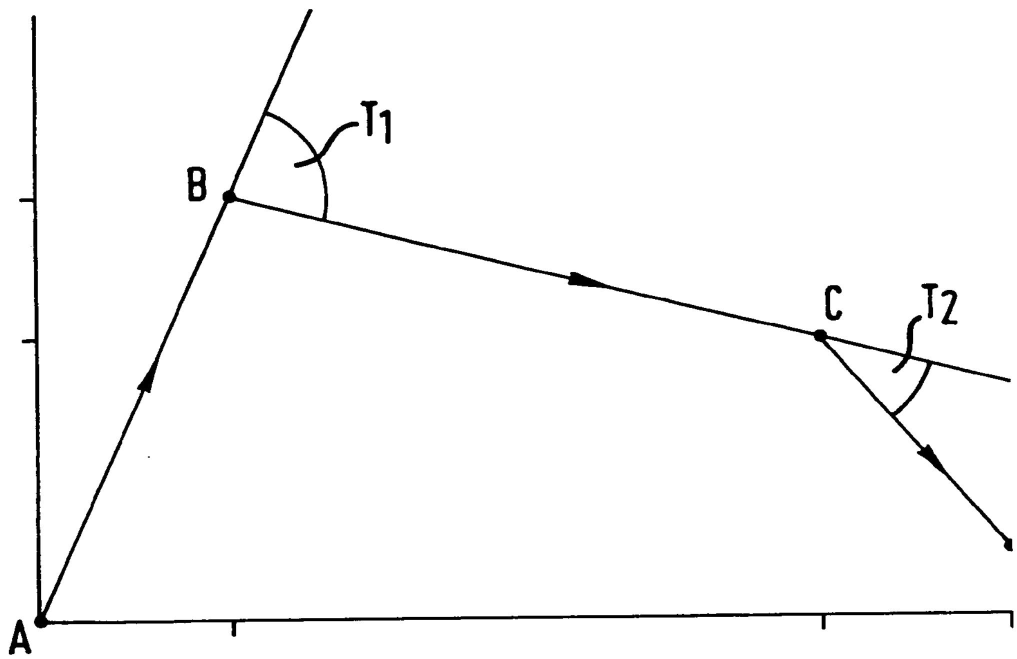

DETERMINE THE NUMBER (N) OF ITERATIONS FOR EACH PATCH
42
CALCULATE POLYGON VERTICES AND NORMALS IN MODELLING SPACE
43
DETERMINE POLYGON RENDERING ORDER FOR EACH PATCH
44
47
LIGHT POLYGONS IN MODELLING SPACE OR RE-USE CALCULATIONS
45
DETERMINE WHICH PATCHES ARE TO BE DRAWN FIRST
46
50
READ NEXT SET OF CONTROL POINTS AND TRANSFORM TO 2D
48
SUBDIVIDE N TIMES
49
SCAN CONVERT TO PIXELS
51
52
MORE PATCHES?
YES
NO
55
FRAME BUFFER
53
WRITE PIXELS TO FRAME BUFFER
54
READ INTERACTIVE INPUT
READ BUFFER
54A
RE-CALCULATE TRANSFORMS
55A

FIG.4




$$\underline{AB}.\underline{BC} = x_{\underline{AB}}\, x_{\underline{BC}} + y_{\underline{AB}}\, y_{\underline{BC}} + z_{\underline{AB}}\, z_{\underline{BC}}$$

$$= \cos T_1$$

FIG.5

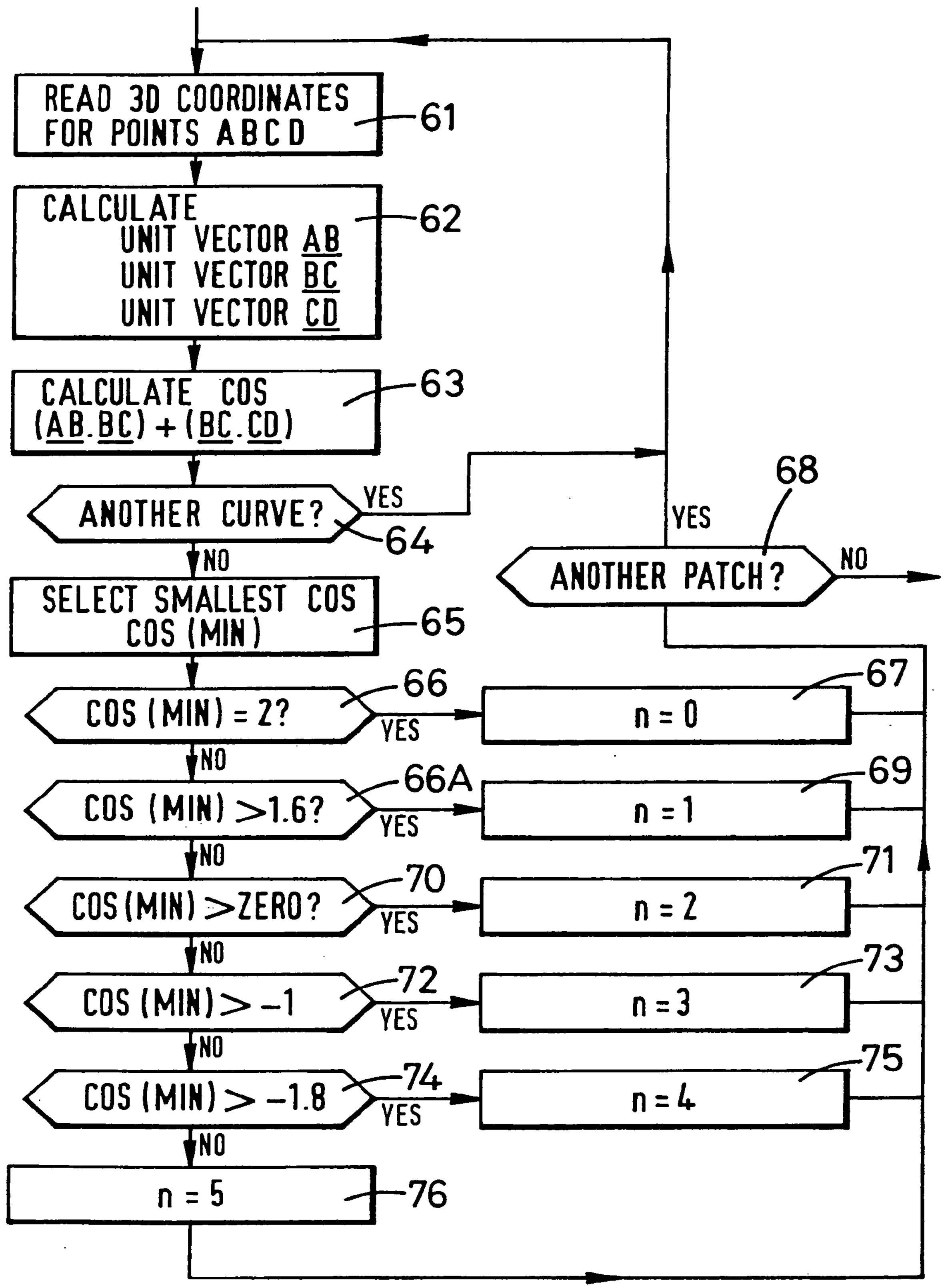

READ 3D COORDINATES FOR POINTS A B C D
61
CALCULATE UNIT VECTOR AB UNIT VECTOR BC UNIT VECTOR CD
62
CALCULATE COS (AB.BC) + (BC.CD)
63
ANOTHER CURVE?
YES
NO
64
SELECT SMALLEST COS COS (MIN)
65
COS (MIN) = 2?
66
YES
NO
n = 0
67
COS (MIN) >1.6?
66A
YES
NO
n = 1
69
COS (MIN) >ZERO?
70
YES
NO
n = 2
71
COS (MIN) > −1
72
YES
NO
n = 3
73
COS (MIN) > −1.8
74
YES
NO
n = 4
75
n = 5
76
ANOTHER PATCH?
68
YES
NO

FIG.6

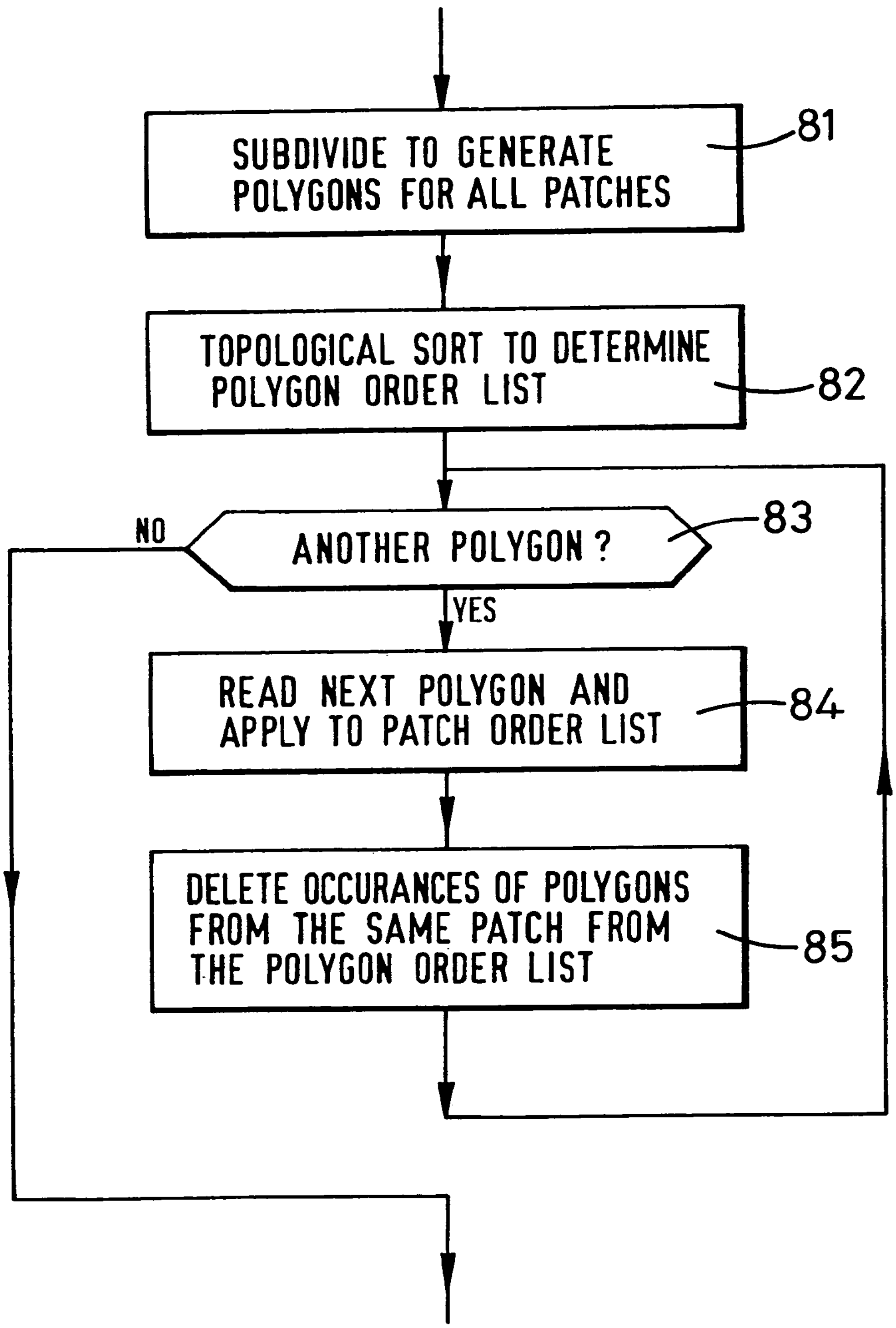

SUBDIVIDE TO GENERATE POLYGONS FOR ALL PATCHES
81
TOPOLOGICAL SORT TO DETERMINE POLYGON ORDER LIST
82
NO
ANOTHER POLYGON ?
83
YES
READ NEXT POLYGON AND APPLY TO PATCH ORDER LIST
84
DELETE OCCURANCES OF POLYGONS FROM THE SAME PATCH FROM THE POLYGON ORDER LIST
85

FIG.7

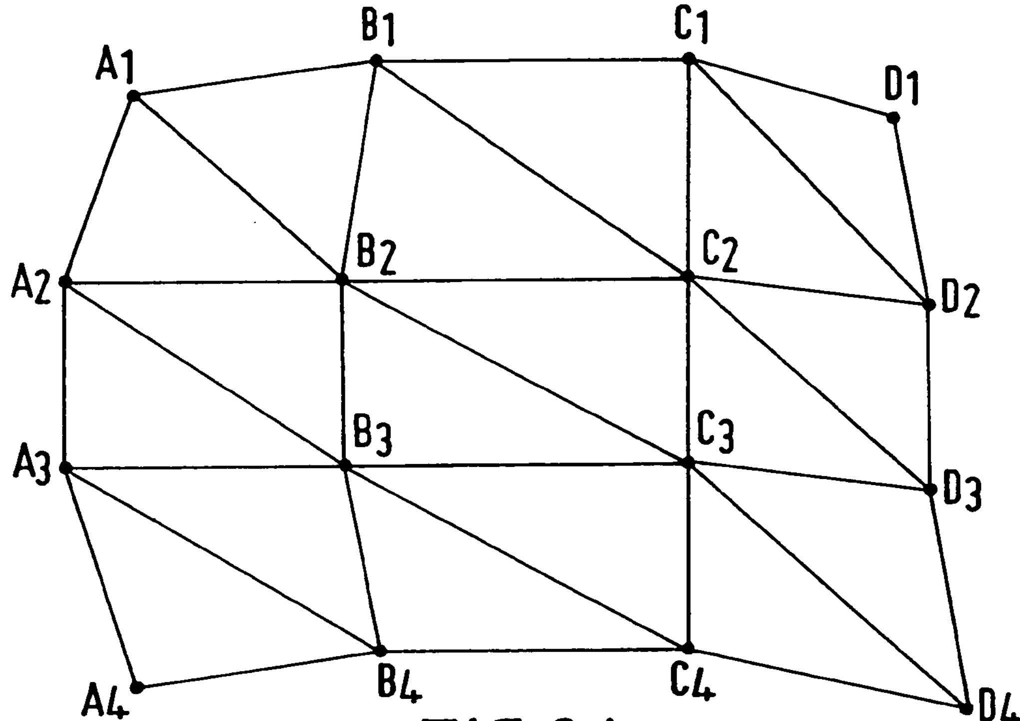



FIG. 8A

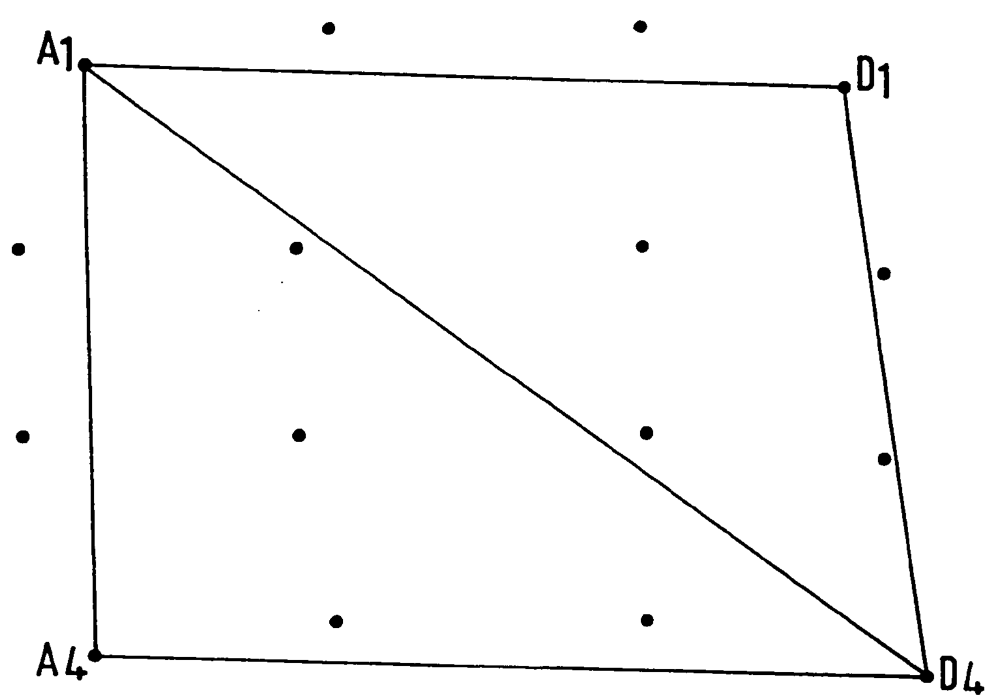



FIG. 8B

European Patent Office

# EUROPEAN SEARCH REPORT

Application Number
EP 93 30 8664

## DOCUMENTS CONSIDERED TO BE RELEVANT

| | Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (Int.Cl.5) |
|---|---|---|---|---|
| 1 | A | EP-A-0 366 463 (TEKTRONIX)<br>* the whole document *<br>--- | 1-20 | G06F15/72 |
| 4 | A | EP-A-0 314 335 (IBM)<br>* page 2, line 2 - line 51 *<br>--- | 2-8,<br>12-18 | |
| 1 | A | PROCEEDINGS FALLJOINT COMPUTER CONFERENCE<br>2 June 1986 , NEW-YORK NY US<br>pages 931 - 940<br>BREEN 'CREATION AND SMOOTH-SHADING OF STEINER PATCH TESSELATIONS'<br>* page 932, right column, line 12 - page 933, left column, line 6 *<br>----- | 1,2,9,10 | |

TECHNICAL FIELDS SEARCHED (Int.Cl.5)

G06F

The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
|---|---|---|
| THE HAGUE | 7 February 1994 | Burgaud, C |

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
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E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

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